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An Experimental and CFD Analysis of Sloshing in a Tanker

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Abstract

Sloshing is a violent resonant fluid motion in a moving tank. When a fluid moves and interacts with its container, the dynamic pressures of such an interaction may cause large deformation in the container wall as well as the supporting structure. Most of the work has been done on rectangular tanks. Moreover in most of the studies numerical approach is used. The present study is focused on the fluid structure interactions in an elliptical tank. The movement of fluid in an elliptical tank has been studied using simulation and experimentation and different baffle configurations are used. The pressure exerted by the fluid on the walls of tank is calculated over a certain period of time. The dynamic response of baffled liquid storage tank has been studied extensively to study the influence of location and shapes of baffles under excitation. Different baffle configurations were examined and role of combination of horizontal and vertical baffles were found to be significant in controlling the sloshing.

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Keywords: Sloshing; Fluid Sturucture Interface; Baffles.

1. Introduction

Sloshing is a violent resonant fluid motion in a moving tank. When a fluid moves and interacts with its container, the dynamic pressures of such an interaction may cause large deformation in the container wall as well as the supporting structure. The motion of liquid arises due to the dynamic motion of the container which can occur under various circumstances. There are two major problems arising in a computational approach to

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sloshing. These are the moving boundary conditions at the fluid tank interface, and the nonlinear motion of the free surface. The main objective of this work is to determine sloshing load effects on fluid container using different baffle configurations. Moreover, the objective is also to validate the results experimentally.

The design of this equipment requires detailed understanding of liquid motion during sloshing. Sloshing can be the result of external forces due to acceleration/deceleration of the containment body. Particular concern is the pressure distribution on the wall of the container reservoir and its local temporal peaks that can reach as in road tankers twice the rigid load value. In road tankers, the free liquid surface may experience large excursions for even very small motions of the container leading to stability problems. This is manifestly the case in design of automotive and aerospace structure as well as modeling the response of offshore structures, long span bridges and high rise buildings. Fluid–structure interaction also plays an important role in the safety assessment of power generation plants and many other industrial purposes. The general topics of fluid–structure interaction is indeed a particularly broad subject in that it simultaneously brings together all the aspects associated with both structural mechanics and fluid mechanics. Each of these two areas are complex by themselves, however, when considered together, the situation becomes even more complex. In fact, interaction (or coupling) between the fluid and solid response can be viewed as a feedback loop. Any motion of the free liquid surface inside its container caused by any disturbance to partially filled liquid container is called sloshing. A fluid partially occupying a moving tank undergoes wave motions (sloshing). These motions generate severe hydrodynamic loads that can be dangerous for structural integrity and stability of rockets, satellites, ships, trucks and even stationary petroleum containers. Civil engineers and seismologists have been studying liquid sloshing effects on large dams, oil tanks and elevated water towers under ground motion. Since early 1960s, the problem of liquid sloshing dynamics has been of major concern to aerospace engineers studying the influence of liquid propellant sloshing on the flight performance of space vehicles. Baffles have been used as passive slosh damping devices in the liquid storage containers.

Over the years, the problem of sloshing has been studied by a number of researchers by using different methods and techniques. To name a few, Salem (2000) investigated that partially filled tankers undergoing turns or lane change maneuvers have a lower rollover threshold than any other type of vehicle [1]. Celebi et al. (2001) investigated nonlinear liquid sloshing inside a partially filled rectangular tank. The fluid was assumed to be homogeneous, isotropic, viscous, Newtonian and exhibit only limited compressibility [2]. Frandsen (2003) studied a fully non-linear finite difference model based on in viscid flow equations [3]. Kyoung et al. (2005) observed that nonlinear sloshing problem can be numerically simulated [4]. Lee et al. (2006) conducted a series of parametric sensitivity studies on unmatched dimensionless scale parameters was carried out on the liquefied natural gas (LNG) tank sloshing loads by using a computational fluid dynamics (CFD) program [5]. Akyildız et al. (2006) observed pressure variations and three-dimensional effects on liquid sloshing loads in a moving partially filled rectangular tank have been carried out numerically and experimentally [6]. Liu et al. (2008) employed numerical model to study three-dimensional (3D) liquid sloshing in a tank with baffles [7]. Eswaran et al. (2008) studied the sloshing waves for baffled and un-baffled tanks [8]. Panigrahy et al. (2008) conducted a series of experiments in a developed liquid sloshing setup to estimate the pressure developed on the tank walls and the free surface displacement of water from the mean static level [9]. Khezzar et al. (2009) had designed a test rig to study water sloshing phenomenon rectangular container subjected to sudden impact [10]. Zheng et al. (2012) studied in-house two-phase fluid flow model by solving Navier-Stokes equations was employed in this study to investigate liquid sloshing phenomena in cubic tank with different baffle configurations under the harmonic motion excitation [11]. Hasheminejad et al. (2014) studied two-dimensional transient sloshing in non- deformable baffled horizontal circular cylindrical vessels, filled with inviscid incompressible fluids to arbitrary depths, and subjected to arbitrary time-dependent later alaccelerations [12]. Nicolici et al. (2013) focused on the sloshing phenomena and on the coupling computational fluid dynamics (CFD) analysis with the finite element stress analysis (FEA) used to predict the sloshing wave amplitude, convective mode frequency, pressure exerted on the walls and the effect of sloshing on the anchoring points forces [13].

2. Problem Formulation

The literature review reveals that lot of work has been reported on rectangular tanks using the numerical and experimental approach. But very less has been reported on elliptical tank or actual scaled model of a liquid transportation tank. So in the present work, effect of various baffle configurations has been studied on the fluid structure interface using two dimensional nonlinear CFD analysis of a scaled model of oil transportation tank. Also the results of CFD analysis are validated experimentally.

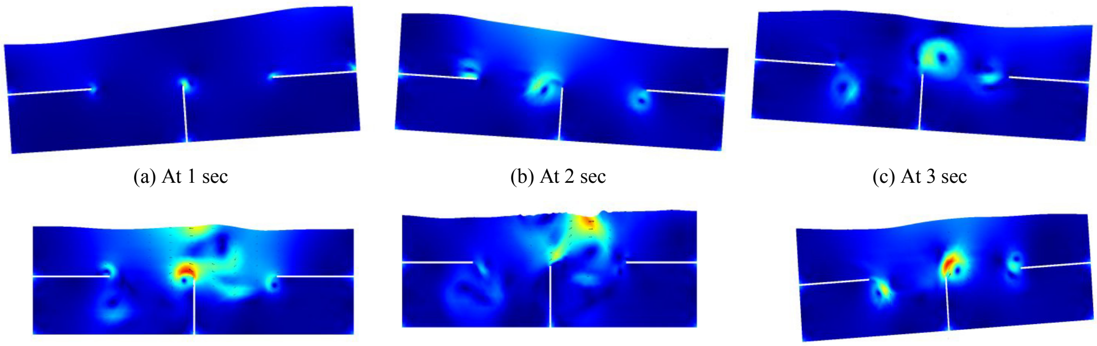
To study the fluid structure interface in a three dimensional elliptical tank, a two dimensional model of the petrol truck is generated in the COMSOL multi-physics. For this dimensions of a standard truck having tank capacity 15000 liter has been taken into account. A scale factor of 1:3 has been used so that the same model can be used for future experimental work. To study the phenomenon precisely fixed triangular mesh is used. In the study various parameters are used reffered from the litrature and considering the real life situations. List of various parameters used are given in Table I.

Table 1. Various parameters used in the study.

S. No.	Parameter	Value	Units
1	Velocity	20	m/sec
2	Gravity	9.814	m/sec^2
3	Density of petrol	737	Kg/m^3
4	Viscosity of petrol	0.6	cP
5	Time taken by the truck to stop	6	Seconds
6	Frequency	1	Hz
7	Maximum angle of inclination	4	Deg

3. Finite Element Analysis

Simulations of the partially filled tank are done in the COMSOL multiphysics software. Before the simulation it has been assumed that the maximum pressure will occure along the maximum cross section therefore maximum sized rectangular area along the two dimensional palne of ellipticle cross section has been taken for the study. First simulation is done without any baffles and fluid is free to move so as to find the maximum pressure exterted by the fluid. A sudden retardation is applied to the tanker and it takes 6 seconds to stop completely. Due to the sudden retardation sudden load is applied. When a container is subjected to linear instability, a series of waves are formed in the liquid and so the liquid gets displaced, and hence exerts a pressure on the walls of the container. For the other simulations combination of horizontal and vertical baffles and vertical baffles are used.

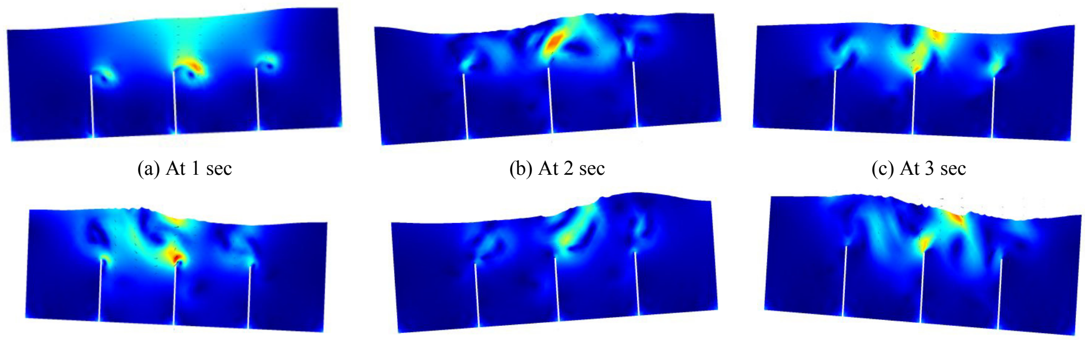


(a) At 1 sec (b) At 2 sec (c) At 3 sec

(d) At 4 sec (e) At 5 sec (f) At 6 sec

Fig. 1. Movement of fluid over the combination of vertical and horizontal baffles at different times.

Various screen shots of the simulation were captured. Fig. 1 and Fig. 2 shows the captured screen shots revealing the motion of the fluid over the different baffle arrangements at different times. Second arrangement is of vertical baffles and the movement of fluid over the baffles is revealed in the simulation as shown in the fillowing screen shots.



(a) At 1 sec (b) At 2 sec (c) At 3 sec

(d) At 4 sec (e) At 5 sec (f) At 6 sec

Fig. 2. Movement of fluid over the vertical at different times.

4. Experimental Setup

To validate the results of CFD analysis experiments with similar baffle configurations were done. Scaled model of elliptical tank is attached to a guide mechanism which helps the tank to move to and fro with the help of a gear box driven by a DC motor. Pressure gauges are attached to the walls of the tank wall. The output of the pressure gages was fed to the channels of the data acquisition system that was coupled to a PC.

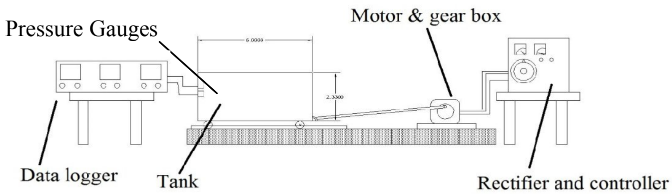


Fig. 3(a). Schematic diagram of experimental setup.

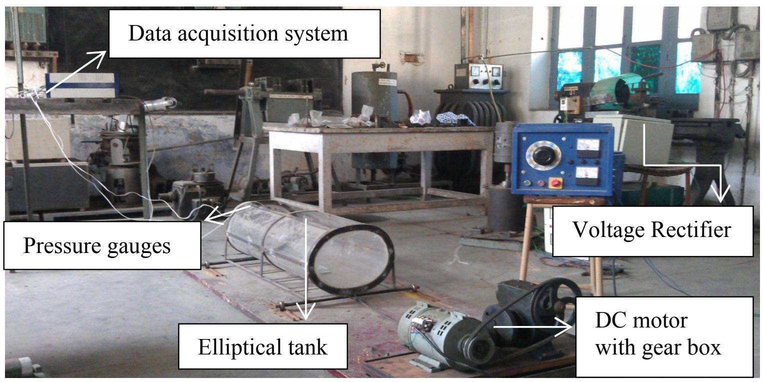


Fig. 3(b). Experimental setup.

Tank is partially filled with the water. When the container is subjected to linear movement, a series of waves were produced. Voltage from the rectifier is varied to vary the speed of motor. Due to displacement of fluid it exerts pressure on the walls of tank.

5. Results

Initially, experiments were conducted without any baffles and series of experiments were incorporated by one horizontal and one vertical baffle and three vertical baffles. It has been found that the severity of sloshing load depends on various factors like depth of fluid, frequency of excitation, motion of tank.

Fig. 4, Fig. 5 and Fig. 6 reveals the effect of baffles on the pressure exerted by the fluid on the walls of tank. Here P1, P2 and P3 are the values of maximum pressure when no baffles are used, two horizontal and one vertical baffle and three vertical baffles respectively.

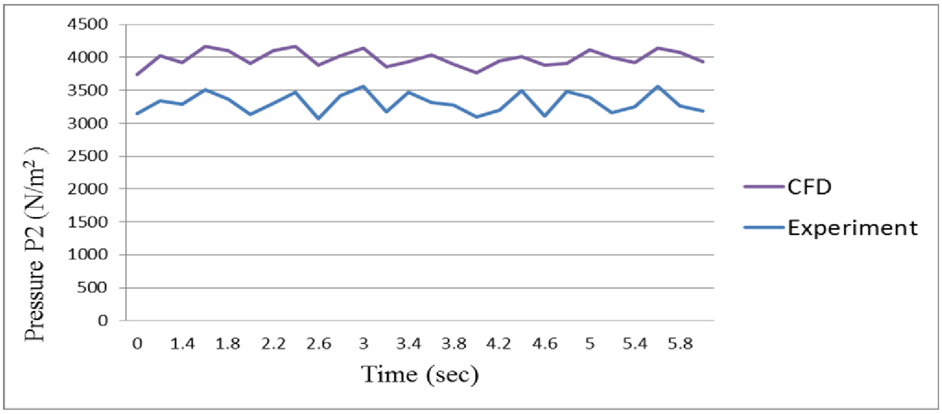


Fig. 4. Pressure variations at tank walls in CFD and experimental analysis with no baffles.

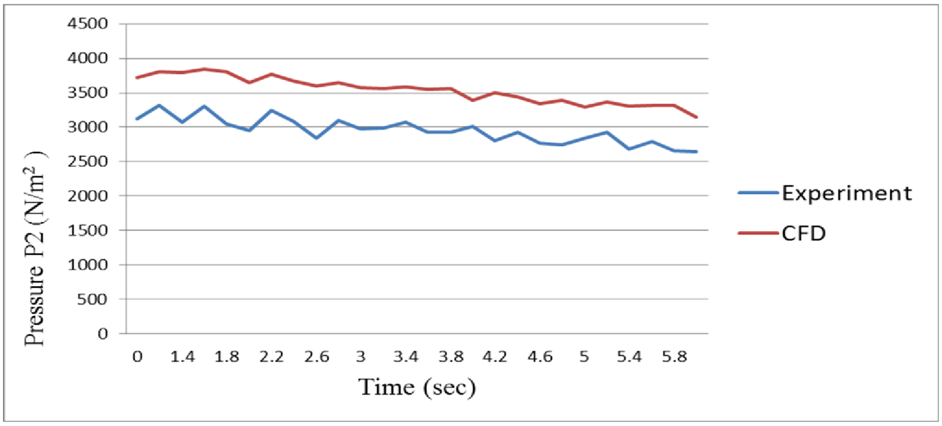


Fig. 5. Pressure variations at tank walls in CFD and experimental analysis with two horizontal & one vertical baffles.

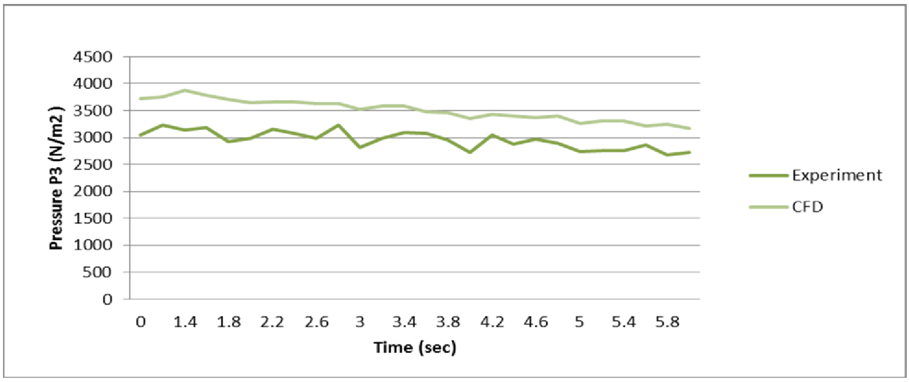


Fig. 6. Pressure variations at tank walls in CFD and experimental analysis with three vertical baffles.

From the present study it has been found that there is no significant variation in the results drawn from CFD analysis and experimentation. The maximum pressure of fluid in the CFD analysis of tank without baffles is 4167.840 N/m^2 and corresponding to that maximum pressure of fluid in the tank with two horizontal and one vertical baffle is 3807.034 N/m^2 and 3888.158 N/m^2 respectively. From the CFD analysis, percentage reduction in fluid pressure in the tank with two horizontal and one vertical baffle is 8.65% and in the tank with vertical baffles is 6.71%.From the experimentation the maximum pressure of fluid in the tank without baffles is 3770.929 N/m^2 and the maximum fluid pressure in the tank with two horizontal and one vertical is 3580.119 N/m^2 and with vertical baffles is 3558.082 N/m^2 respectively. It has been observed that the percentage reduction in fluid pressure in the tank with one vertical and two horizontal baffles is 5.06% and in the tank with vertical baffles is 5.64%. From the above results it is clearly seen that there is significant variations in the results of CFD analysis and experiment results. There are a number of reasons which results in the variation in the results. Some of the reasons are as follows:

a) Boundary conditions may vary during experimental work.
b) Loading conditions- In CFD analysis the tank is filled up to 90% but this value may vary during the experimental work.
c) Friction is not taken into account.
d) Properties- the properties of tank material are not taken into account. Moreover there may be some variation in the fluid properties used for the experimental work.

6. Conclusions

The objective of this paper is to investigate the effect of different baffle configurations on the sloshing loads. To investigate this CFD analysis and experimental investigation is done so as to validate the results. The results from CFD and experiment were compared. From the study it can be concluded that configuration of baffles effect the average and maximum pressure developed in the walls of the road tanker. The reduction of fluid pressure on the walls of container is 8.65% and 5.06% is observed in the case of one vertical and two horizontal baffles. It can also be concluded that combination of horizontal and vertical baffles is more effective in controlling the sloshing than vertical baffles.

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